MONITORING THE SPATIALLY AND TEMPORALLY COMPLEX ACTIVE DEFORMATION FIELD IN THE SOUTHERN BAY AREA

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1. Investigations Undertaken

The southern Bay Area is a structurally complex region of the North American-Pacific plate margin. Geodetic measurements reveal a spatially complex deformation field with evidence for time-dependent strain that may affect the timing of future earthquakes in the Bay Area. Although the general nature of the plate boundary (right-lateral strike-slip distributed between the major strike-slip faults with small amounts of contraction) is relatively unambiguous, several specific areas exhibit behavior that suggests structural complexities.

Since the 1989 Loma Prieta earthquake, we have performed repeated Global Positioning System (GPS) surveys and found significant differences between the active displacement field and that measured in the preceding two decades using Electronic Distance Measuring (EDM). The pattern of deformation suggests significant postseismic contraction across the youthful southern Santa Cruz Mountains northeast of the San Andreas fault (SAF). We monitor the details of anomalous post-seismic strain pattern by continuing to collect geodetic data from the southern Bay Area GPS network. Our own measurements are complemented by GPS data collected by the U.S.G.S. crustal deformation group. New stations have been added to the GPS network to more closely monitor deformation near the transition from locked to creeping behavior of the SAF near San Juan Bautista.

We integrate our GPS data with other data sets such as the creepmeter records on the

Hayward, Calaveras and San Andreas faults (Data collected by USGS, and CU Boulder) as well as borehole strain data from instruments installed near San Juan Bautista (CSIRO and USGS). We are also integrating differential interferometric synthetic aperture (InSAR) measurements with the GPS data, with very promising results along the Hayward fault (Bürgmann et al., 1998; Bürgmann et al., 2000). and subsurface fault slip rates inferred from repeating micro-earthquakes (Nadeau and McEvilly, 1999, Bürgmann et al. 2000)

Studies of seismicity at Parkfield, CA reveal a systematic organization in space and time, dominated by clustering of nearly identical, regularly occurring microearthquakes ('characteristic events') on 10-20 m wide patches within the fault zone (Nadeau and McEvilly, 1999). In general, recurrence intervals (0.5 to 2 yr.) scale with the magnitude of the repeating events for the magnitude range available (Mw 0.2 to 1.3). Clusters of these characteristic events occur throughout the slipping fault surface. Measurements of the moment release rate allow estimates of the seismic parameters source area, slip, and recurrence interval. Nadeau and McEvilly (1999) show that it is possible under reasonable assumptions to infer the spatial distribution of variations in slip-rate on the fault surface from the changes in recurrence intervals for the characteristic event sequences. Bürgmann et al. (2000) applied this technique to the northern Hayward fault and find evidence for aseismic slip throughout all depths of the segment, further substantiating the results of a formal inversion of GPS and InSAR data.

The primary objective of this project is to monitor the spatially and temporally complex active deformation field in the southern Bay Area. This report will focus on three aspects of this investigation:

- Update of GPS measured crustal deformation.
- The use of InSAR to determine slip rates on shallowly slipping members of the SAF system.
- The inclusion of repeating micro-earthquake data to determine subsurface slip rates on aseismically slipping fault segments.

2. Results

GPS Data. The southern San Francisco Bay Area GPS network consists of several profiles across the SAF system and additional arrays localized around areas of particular interest. The Black Mountain, Loma Prieta, and Monterey profiles are part of a larger network established by the U.S. Geological Survey that consists of six GPS profiles across the SAF system and the 5-station Loma Prieta Monitor network. To improve the spatial resolution of the displacement field following the Loma Prieta event, we yearly reobserve a 22-station GPS network (Santa Cruz Mountains network) near the epicenter. We have also densified our occupations in the Pajaro region at the transition region to the creeping San Andreas fault segment, along the Calaveras fault, and surrounding the Hayward fault.

GPS data from the southern Bay Area is processed using the Bernese GPS processing software (Version 4) developed at the University of Bern. Continuous data collected through the BARD network are processed with campaign data collected for this project during the same time period. We combine the survey-mode data collected by the crustal deformation groups at Stanford University, the University of California, Berkeley, and the USGS with monthly solutions of the BARD network processing at the Berkeley Seismological Laboratory to compute the final velocity field shown in Figure 1. Figure 1 shows the GPS network that was monitored for long enough to produce reliable velocity estimates. We excluded data affected by the Loma Prieta postseismic transient to plot the estimates of secular motions shown in this figure.

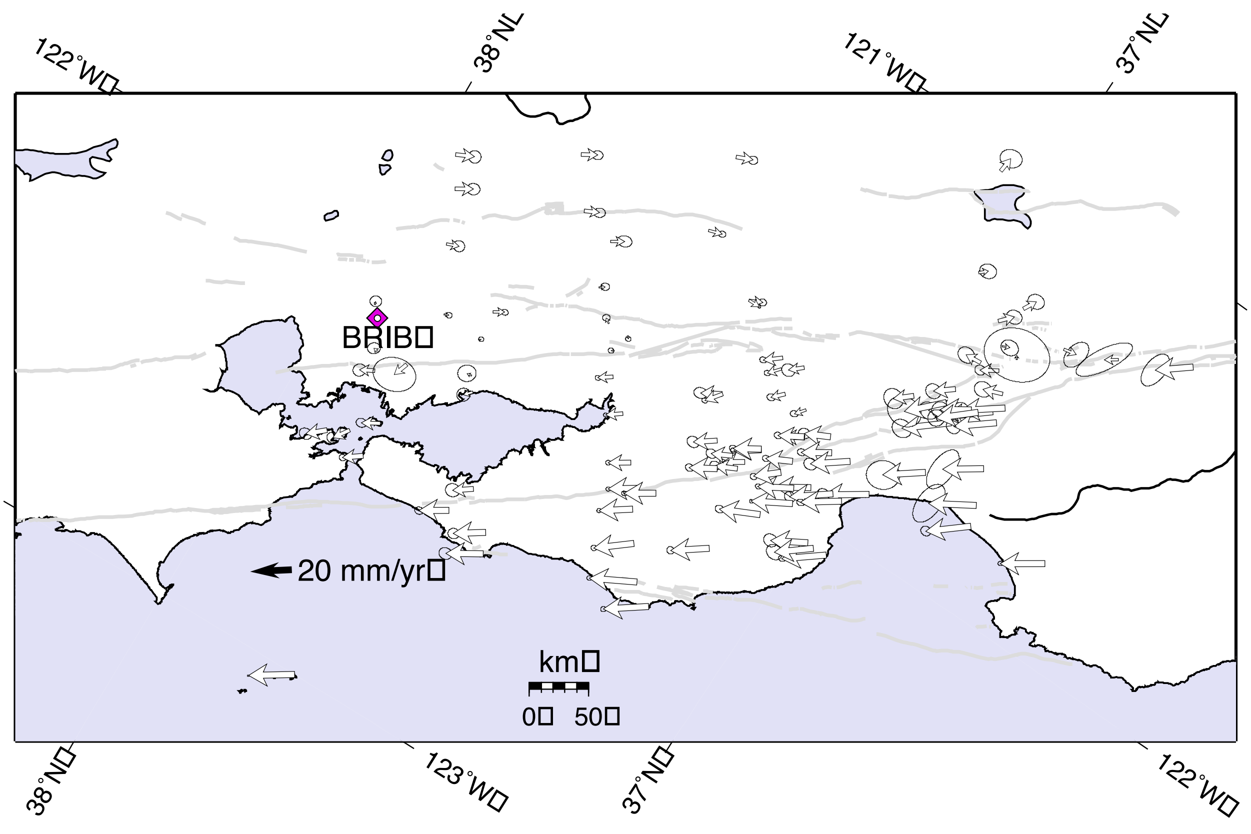


Figure 1. Compilation of continuous and campaign GPS derived velocity field in oblique Mercator projection about the pole of Pacific plate to SNGV block rotation. Data are from our own and USGS measurements. The displacement field, shown relative to BARD station BRIB, widens north of Monterey Bay as slip is being transferred to the Calaveras-Hayward fault zone. The velocities of the Pacific plate and the SNGV block determined from VLBI (Argus, 1996, written commun.) show that virtually all plate motion occurs across the Bay area. Across the width of the GPS network about 38 mm/yr of motion are distributed among fault system.

Shallow fault slip on Bay area faults from InSAR measurements. Geodetic measurements of surface displacements surrounding a fault can be used to determine subsurface slip rates on dislocations in an elastic half-space model. If fault slip occurs at relatively shallow depth, as is the case for faults experiencing creep in the upper 10 km of the crust, such measurements have to be closely spaced near the fault. However, precisely surveyed GPS sites in the San Francisco Bay area are generally spaced more than 10 km apart and it is therefore difficult to determine a reliable slip estimate from existing point measurements alone. Space based interferometric synthetic aperture radar (InSAR) can map ground deformation at 10s-of-meter spatial resolution with sub-cm precision. InSAR only provides measurements of one component of the displacement field along the look direction of the radar. Thus, to improve constraints on the rate and extent of aseismic fault slip, we integrate surface creep rates established over several decades, GPS measurements of site velocities, and InSAR measured range changes. We also consider subsurface creep rates estimated from identical repeating micro-earthquakes as discussed in the following section of this report.

We use synthetic aperture radar (SAR) data collected by the European Space Agency's ERS spacecraft since 1992 to produce high-resolution surface deformation maps of range change to the spacecraft. We use InSAR data analysis techniques developed at the Jet Propulsion Laboratory. Surface displacement rates are computed from the interferograms by unwrapping angular phase delays and converting the phase delay into line-of-sight range change rates. The ERS descending orbit track trends 193.9° with the radar looking westward at a 23° off-vertical look angle. Surface displacements and resulting range change are related as $\Delta\rho = \Delta\vec{d} \cdot \vec{e}$, where $\Delta\rho$ and $\Delta\vec{d}$ are the range change and surface displacement vectors, respectively, and $\vec{e}$ is the unit vector in the range direction (Bürgmann et al., 2000). Topographic contributions to the apparent range changes are removed using a 30-m-resolution U.S. Geological Survey digital elevation model. We remove a linear displacement gradient across the SAF system, which is well constrained by the GPS velocities, from the InSAR range change data before flattening (removal of orbital ramp during processing). This interseismic deformation ramp is added back into the interferogram during the final processing steps.

The utility of InSAR depends on surface properties being coherent between the pair of scenes used to form the interferogram. Any change in surface properties due to vegetation, erosion, or land use will impact the quality of the InSAR measurement (Bürgmann et al., 2000). Densely vegetated areas and rough topography away from mostly developed areas limit the region of adequate correlation. Thus we find that while conditions in the urban Bay area along the Hayward fault are suitable for InSAR (Bürgmann et al., 1998, 2000), it is more difficult to acquire useful data along much of the Calaveras and San Andreas faults.

Figure 2A shows a one year interferogram (August 18, 1997- October 12,1998) of the southern San Francisco Bay area. Much of the range change in the Diablo range and other rough terrain appears to be due to topography-correlated atmospheric noice. In the town of Hollister a sharp range change gradient appears to correlate with the Calaveras fault that is known to actively creep at rates of 10-15 mm/yr, also clearly evident in offset curbs and buildings. However, the localized nature and magnitude of the apparent offset suggests that this offset might in part reflect deformation associated with differential land subsidence across the Calaveras fault due to aquifer recharge and withdrawal. Much of the interferogram in this region, however, is very noisy or incoherent and no clear offsets can be mapped out along the San Andreas fault at this level of processing. We are now evaluating 14 additional interferograms of the region and will attempt to optimize filtering routines to maximize the resolution of the interferograms and to investigate if any tectonic signal can be clearly resolved.

Figure 2B shows a 1992-1995 interferogram (see also Bürgmann et al., 1998) together with GPS data near the southern Hayward fault. We have successfully demonstrated the utility of formally combining InSAR and GPS data together with repeating microearthquakes to resolve the depth of creep along the northern Hayward fault (Bürgmann et al., 2000). With new data from additional sites (including surveys of USGS borehole strainmeters we began surveying in 1998) we hope to resolve slip at depth in a similar fashion on the southern Hayward fault and other southern Bay area faults that have significant aseismic slip.

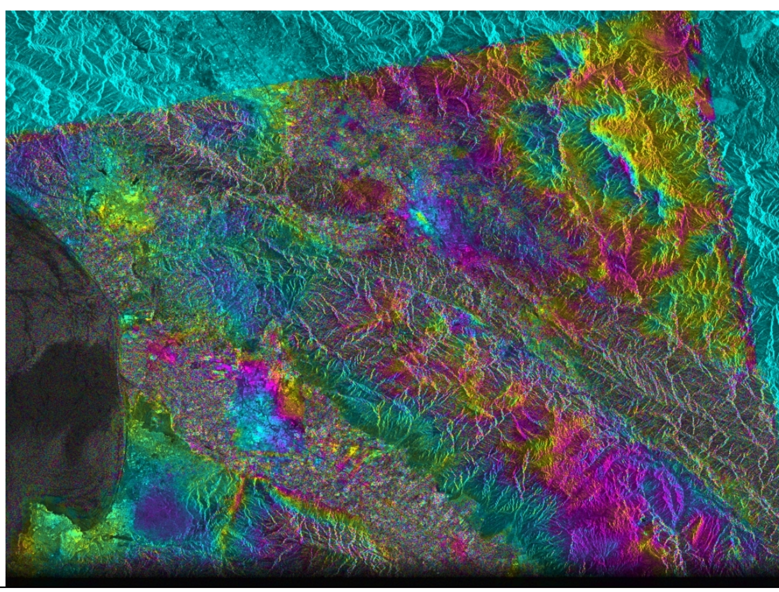
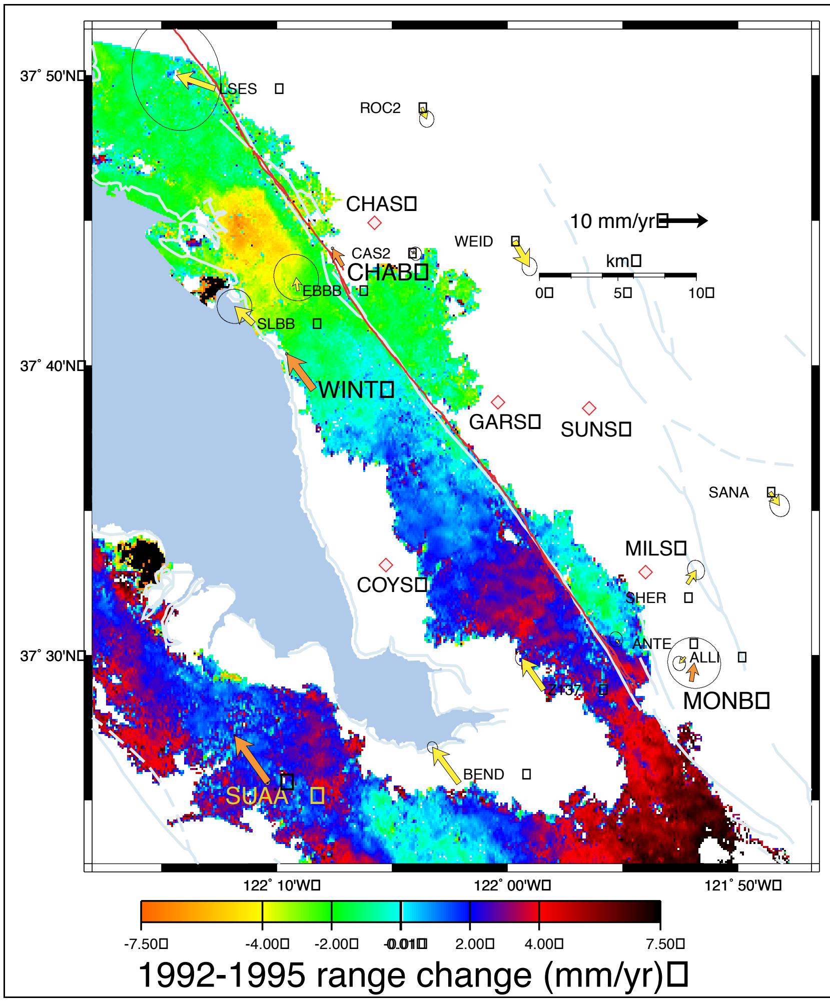


Figure 2. InSAR analysis of the southern Bay area. (A) August 18, 1997- October 12,1998 interferogram from the ERS descending orbit track 299 frame 2871. Note the sharp range step across the Calaveras in Hollister (coherent region in the upper center of the interferogram).



(B) June 10, 1992- November 10, 1995 interferogram, which has been unwrapped to depict range change in mm/yr (ERS Track 70, Frame 2853; orbits 4724 and 22603). Also shown are GPS velocities (arrows tipped with 95% confidence ellipses). Red diamonds indicate USGS borehole strainmeters. Starting in 1998, we have included surveying the monumented strainmeters as part of our monitoring effort to densify the measurements. Our results from InSAR measurements are published in Bürgmann et al., 1998 and Bürgmann et al. 2000.

Time dependent creep of the SAF near San Juan Bautista from repeating micro-earthquakes. Our investigation of transient deformation processes focuses in particular on the SAF near San Juan Bautista at the transition to mostly aseismic creep on the central SAF segment. We have densified our GPS observations in this region for the last several years, as this is an area where slip is accommodated both during moderate size earthquakes and by aseismic creep, sometimes in the form of slow earthquake events. The GPS data (Figure 1) are complemented by creepmeter data collected by the USGS along the SAF and by EDM data collected in the Pajaro network (Mueller and Johnston, 1997) and throughout the Bay Area before 1989 (Lisowski et al., 1991). Nonetheless, our model inversions of the geodetic data from different time intervals shows that while we recognize a pattern of decaying slip since the 1989 Loma Prieta earthquake it is difficult to resolve much detail of the spatio-temporal distribution of the accelerated creep. Our preliminary results suggest that there was an episode of accelerated slip at depth below the Pajaro segment of the San Andreas fault, presumably triggered by stress changes during the earthquake (Wilber and Bürgmann, 1999). We are currently refining our model inversions and are further testing the resolution power of these models.

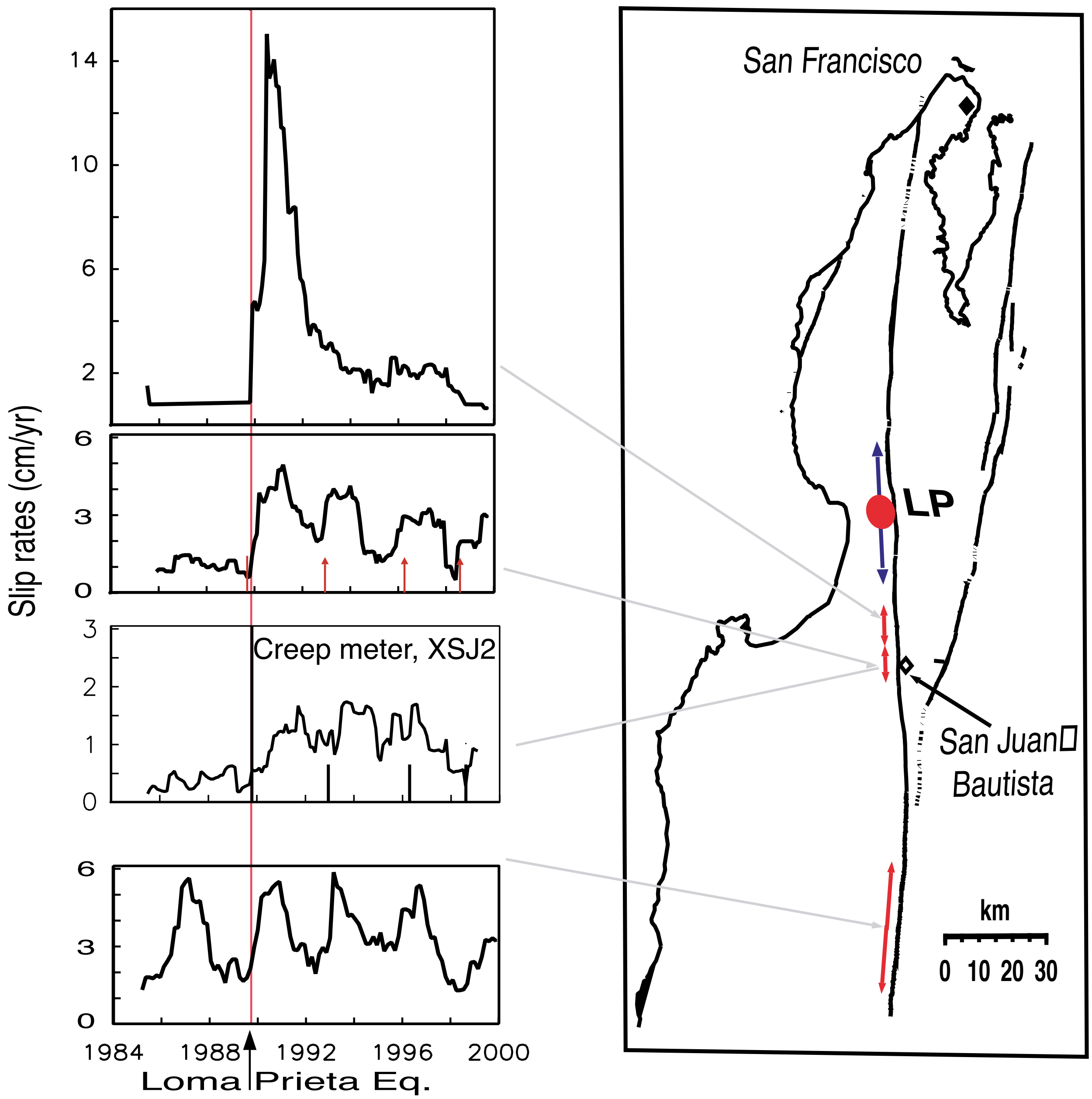


Figure 3. Creep rate variations along the SAF near San Juan Bautista and along the central creeping segment of the SAF. Slip rates (cm/yr) are determined from repeating micro-earthquake sequences (Nadeau, 2000, unpublished results) using methods of Nadeau and McEvilly, developed at Parkfield) and USGS creepmeter data. Vertical line indicates time of Loma Prieta earthquake. The top panel suggests rapidly decaying afterslip in the southeastern portion of the Loma Prieta aftershock zone. Red arrows on the second panel show occurrence of slow earthquakes deduced primarily from strain data (e.g., Linde et al. 1996, Nature, 383, 65-68). Note that slip rate appears to be quasi-periodic with an approximate 3-year period in the southern data sets.

Following the successful comparison of repeating earthquake data with geodetic measurements at Parkfield (Nadeau and McEvilly, 1998) and along the northern Hayward fault

(Bürgmann et al., 2000), we are now working on integrating geodetic and seismic data in a similarly complementary way along the San Andreas fault. Higher slip rates and rapidly varying slip since 1989 makes this fault segment particularly suitable for this type of analysis. Figure 3 shows preliminary results of Nadeau [2000, unpublished results] that indicate the additional constraints provided by repeat frequencies of identically repeating micro-earthquakes. The seismic data allows for a much more detail of spatial and temporal patterns than is achievable with the current geodetic data set.

To the northwest of San Juan Bautista, slip rates decayed from as much as 15 cm/yr right after the earthquake to 2 cm/yr in 1994. The repeater slip rates and and their temporal decay is comparable to that found by Segall et al. (2000) based on a network inversion filter analysis of our 1989-1997 GPS data. Near San Juan Bautista, the temporal pattern of creep-rate is compatible with that measured at a USGS creepmeter there, but the slip rate at seismogenic depth appears higher than that observed at the surface. Here, and further to the southeast, slip rates apparently increased repeatedly at periods of about 3 years. The initiation of rapid creep appears to coincide with episodes of moderate earthquakes or so-called slow earthquakes that occurred in 1992, 1996 and 1998 in the region. The cause of this "pulsing" nature of fault creep along the SAF is still to be determined. We will further evaluate the time dependent fault slip behavior along the SAF from San Juan Bautista to Parkfield to better understand the pattern and mechanisms of the time dependent slip. Intensified monitoring of crustal deformation in this region, through combined use of space geodetic, surface creep, strain, and seismologic data, promises to reveal fundamental information about fault behavior and interaction.

3. Non-technical Summary

We use the Global Positioning System (GPS), Synthetic Aperture Radar Interferometry (InSAR), and repeating indentical micro-earthquakes to gather information on crustal deformation and earthquake hazard in the southern San Francisco Bay region. The data indicate overall post-earthquake relaxation of deformation rates in the region surrounding the rupture area of the 1989 Loma Prieta earthquake. Most of the transient deformation apparently ceased by about 1994, however, transient deformation anomalies apparently persist along the transition region to the creeping San Andreas fault.

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5. Data Availability

Raw and RINEX formatted GPS data files for static surveys of markers in south San Francisco Bay area from 1994-99. These files typically include greater than six continuous hours of data, recorded at a 30 second collection rate with a 10-degree elevation mask. These data are currently archived at the UNAVCO archive facility in Boulder, and also at the University of California, Berkeley. Photocopies of survey log sheets and site descriptions are also available.

Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

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